

V391 Peg: identification of the two main pulsation modes from ULTRACAM $u'g'r'$ amplitudes*

R. Silvotti^{1, **}, S. K. Randall², V. S. Dhillon³, T. R. Marsh⁴, C. D. Savoury³, S. Schuh^{5, 6}, G. Fontaine⁷, and P. Brassard⁷

¹ INAF–Osservatorio Astronomico di Torino, strada dell'Osservatorio 20, 10025 Pino Torinese, Italy

² European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany

³ Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK

⁴ Department of Physics, University of Warwick, Coventry CV4 7AL, UK

⁵ Georg-August-Universität Göttingen, Institut für Astrophysik, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany

⁶ Institut für Astronomie und Astrophysik, Kepler Center for Astro and Particle Physics, Eberhard-Karls-Universität, Sand 1, 72076 Tübingen, Germany

⁷ Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec H3C 3J7, Canada

Received 16 Apr 2010

Published online later

Key words stars: horizontal-branch – stars: individual (V391 Peg)

V391 Peg (HS 2201+2610) is an extreme horizontal branch subdwarf B (sdB) star, it is an hybrid pulsator showing p - and g -mode oscillations, and hosts a $3.2/\sin i$ M_{Jup} planet at an orbital distance of about 1.7 AU. In order to improve the characterization of the star, we measured the pulsation amplitudes in the $u'g'r'$ SLOAN photometric bands using ULTRACAM at the William Herschel 4.2 m telescope and we compared them with theoretical values. The preliminary results presented in this article conclusively show that the two main pulsation periods at 349.5 and 354.1 s are a radial and a dipole mode respectively. This is the first time that the degree index of multiple modes has been uniquely identified for an sdB star as faint as V391 Peg ($B=14.4$), proving that multicolor photometry is definitely an efficient technique to constrain mode identification, provided that the data have a high enough quality.

© 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

About half of field sdB stars, which reside in binary systems, can form through common envelope ejection or stable Roche lobe overflow (Han et al. 2002, 2003). It is more difficult to explain the formation of a single sdB star. Two scenarios are possible: the merger of two low-mass helium white dwarfs and an early hot helium flash; but both are not fully consistent with the observations. A recent review on these arguments is given by Heber (2009). Another possibility, suggested by Soker (1998), is that the huge mass loss needed to form an sdB star is triggered by low-mass bodies, planets or brown dwarfs (BDs). Although this possibility has not been tested by detailed models yet, a planet to the pulsating sdB star V391 Peg (Silvotti et al. 2007) and three circumbinary planets/BDs to the eclipsing sdB+M systems HW Vir (Lee et al. 2009) and HS 0705+6700 (Qian et al. 2009) suggest that sdB planets/BDs could be a relatively common phenomenon (see also Bear &

Soker 2010). A systematic search for sdB substellar objects around 4 sdB stars using the timing method is the main goal of the EXOTIME project (Schuh et al. 2010, Benatti et al. 2010).

V391 Peg (HS 2201+2610) is a particularly interesting system formed by an sdB star and a $3.2/\sin i$ M_{Jup} planet orbiting the host star in 3.2 years at a distance of about 1.7 AU (Silvotti et al. 2007). The sdB star is a hybrid pulsator showing p and g -mode oscillations at the same time (Østensen et al. 2001, Lutz et al. 2009), offering a unique opportunity to characterize the host star through asteroseismic methods. A preliminary mode identification of the higher pulsation frequencies (p -modes) was proposed in Silvotti et al. (2002): the two main pulsation periods of 349.5 and 354.1 s could be reproduced with $l=0$ ($k=1$) and $l=1$ ($k=1$) respectively. However this solution was not unique due to the small number of detected frequencies and other solutions could not be excluded.

* Based on observations obtained at the 4.2 m WHT

** e-mail: silvotti@oato.inaf.it

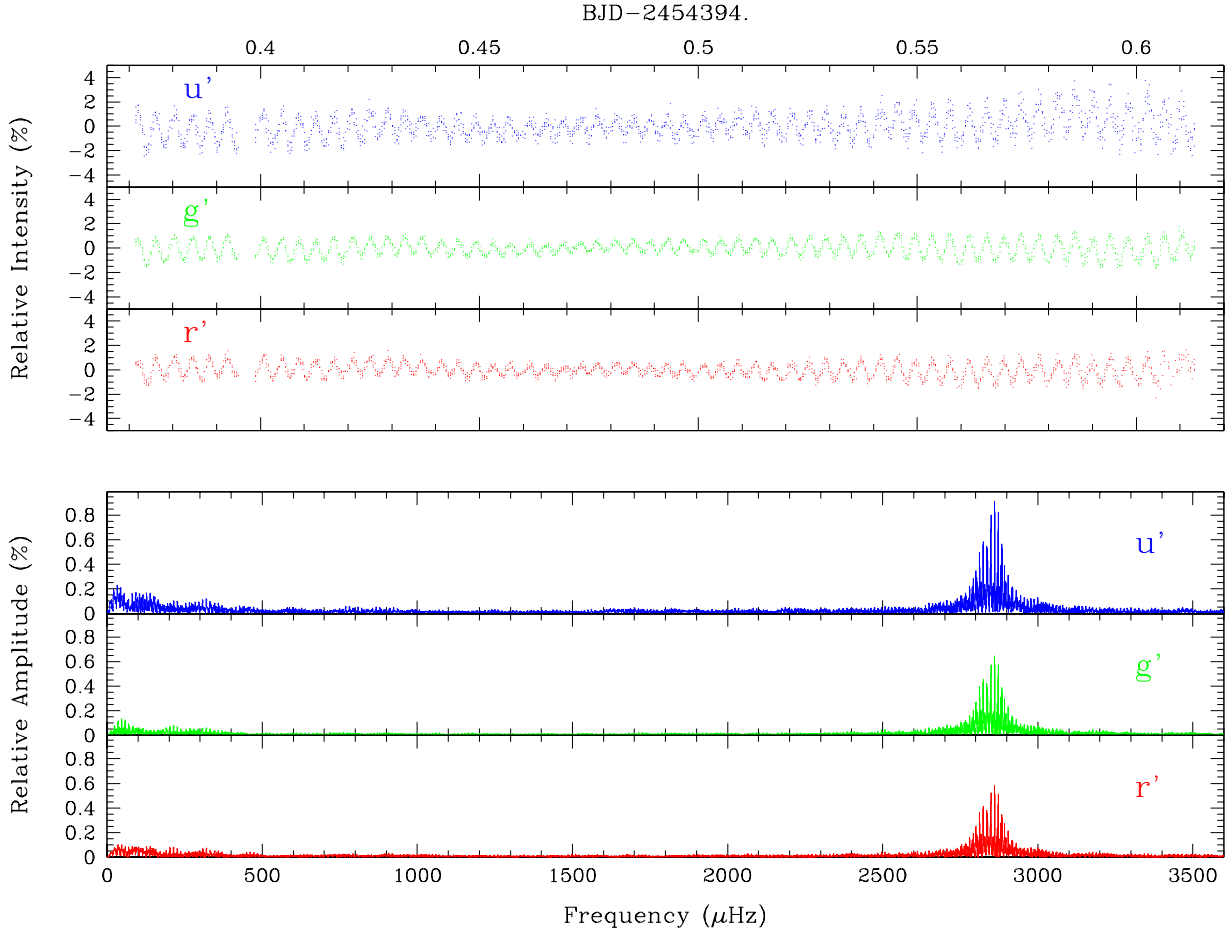


Fig. 1 Upper panels: representative $u'g'r'$ light curves (20 October 2007), with beating effects clearly visible. Lower panels: amplitude spectra of the whole 8-nights run showing the two regions of excited p - and g -modes.

2 Observations, reduction and analysis

V391 Peg was observed for 8 consecutive nights, from October 16 to 23, 2007, using ULTRACAM (Dhillon et al. 2007) at the 4.2 m William Herschel telescope (WHT). In total we collected 260,592 exposures in three photometric bands ($u'g'r'$) of the SLOAN system, with exposure times between 1.2 and 1.6 s and a dead time of only 25 ms between one frame and the next. The reduction was performed using the ULTRACAM pipeline (see, for example, Littlefair et al. 2008), including bias and flat field correction and aperture photometry. Then we computed differential photometry, dividing the target's counts by the counts of a comparison star, we binned the data to an effective exposure time of 10 s and we performed a correction for the residual extinction. The last step is crucial for the g -modes which have periods of ~ 0.5 -2 h and are particularly disturbed by variations that occur on similar time scales. Finally we applied the barycentric correction to the times. More details regarding observations and data reduction will be given in a forthcoming paper (Silvotti et al. in preparation). At the end of the

process, for each filter we obtained a single file with 2 columns: barycentric julian date and fractional brightness variation.

These files were analyzed using Period04 (Lenz and Breger 2005) in order to determine the pulsation frequencies and the amplitudes in the different bands. A portion of the light curves and the amplitude spectra in the three photometric bands are shown in Fig. 1. The frequencies obtained were compared with those obtained from previous runs and indeed we found a perfect agreement except for f4 and f5: the value 2921.816 μHz found previously for f4 (Silvotti et al. 2002) is now 2910.272 μHz , indicating that the old value was a 1-day alias of the correct frequency. The new value of f4 is confirmed by two other independent runs with high frequency resolution at the 3.6 m TNG (August 2008) and 1.3 m MDM (October 2007) telescopes (Silvotti et al. in preparation). F5 (2738.015 μHz , Silvotti et al. 2002) is not found in any of the new observations and the WHT/ULTRACAM data suggest 2 new low-amplitude frequencies. An updated list of frequencies, including also the low-frequency g -modes, will be published (Silvotti et al. in preparation).

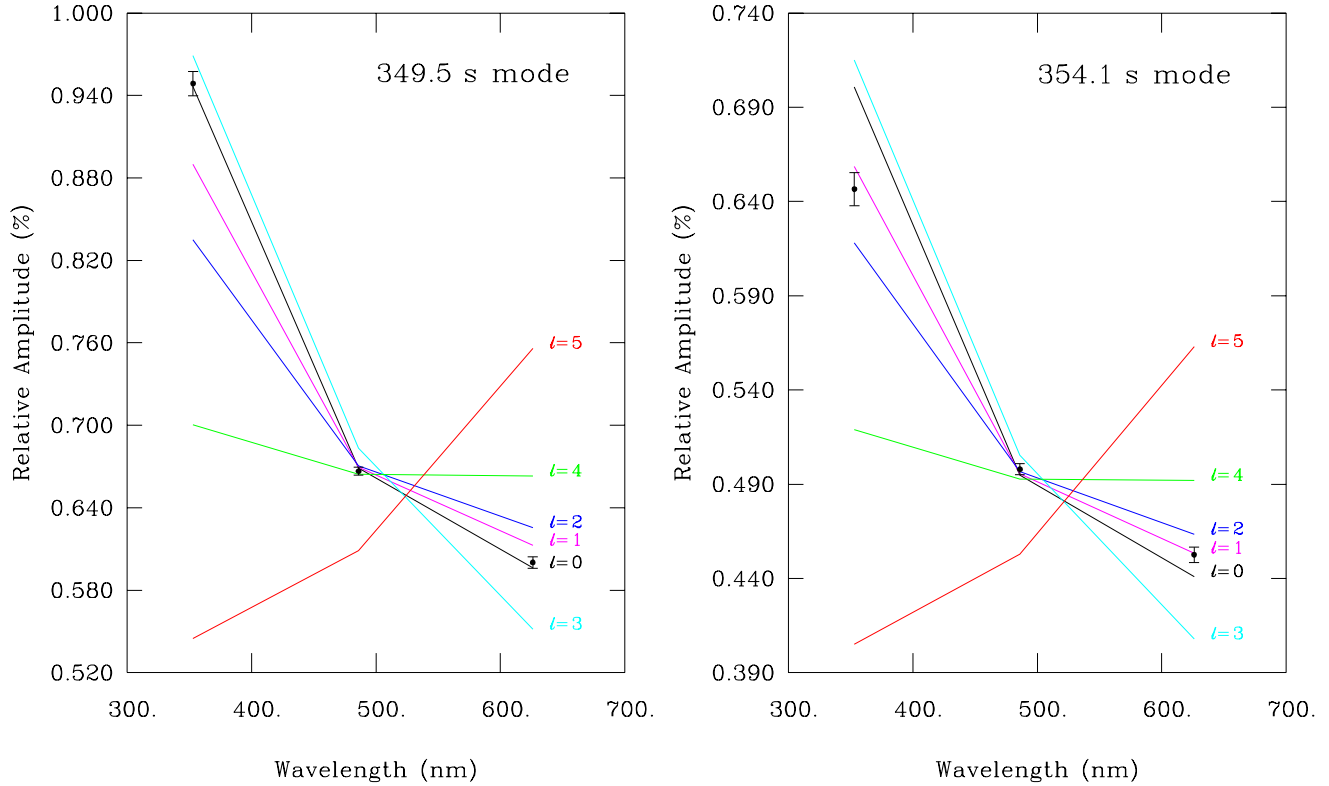


Fig. 2 Fit to the two dominant modes of V391 Peg, including non-adiabatic effects.

Using the improved list of frequencies, we measured the amplitudes of the various frequencies by means of least-square sinusoidal fits. In this paper we concentrate only on f1 and f2, for which the errors on the amplitudes are sufficiently small to obtain significant results.

3 Comparison with theoretical amplitudes and mode identification

The amplitudes obtained have been compared with theoretical amplitudes calculated following the same procedure as described in Randall et al. (2005). As input we took the atmospheric parameters from Østensen et al. 2001 ($T_{\text{eff}}=29,300$ K, $\log g=5.4$). With the very small error bars of the ULTRACAM amplitudes, the quality of the fit is very sensitive to the exact input values of the atmospheric parameters. However, taking into account the T_{eff} $\log g$ uncertainties, we never obtain any change in the mode identification. The same is true when we use slightly different atmospheric parameters obtained by one of us (G.F.) on the basis of spectra acquired at the 90 inch telescope at Kitt Peak ($T_{\text{eff}}=30,000$ K, $\log g=5.46$) or at the MMT ($T_{\text{eff}}=29,900$ K, $\log g=5.51$), made available to us by Betsy Green (private communication).

The monochromatic atmospheric quantities were then convolved over the ULTRACAM filters, taking into account the filter response curves as well as the quantum efficiency of the CCDs, and the transparency curve for a representative observatory site (we used Cerro Tololo which is at a similar altitude as the La Palma observatory).

Non-adiabatic effects were computed as they significantly influence the theoretical colour-amplitudes. They were estimated using the equations given in Randall et al. (2005) from the adiabatic and non-adiabatic eigenfunctions calculated from second generation envelope models (Charpinet et al. 1997), using the following stellar parameters: $T_{\text{eff}}=29,300$ K, $\log g=5.4$, total stellar mass $M_*=0.48 M_{\odot}$ and fractional thickness of hydrogen-rich envelope $\log q(H)=-2.95$, although the two last values do not really influence the results much, as long as they take on reasonable values. The model was then analysed with adiabatic and non-adiabatic pulsation codes, and the non-adiabatic quantities R and Ψ_T (defined in Randall et al. 2005) were computed for the period spectrum of the model. Since R and Ψ_T are not dependent on the degree index while they depend quite strongly on the period of the mode in question, their value were interpolated in period space to find their optimal values for the observed periods.

The wavelength-integrated atmospheric quantities and the non-adiabatic parameters were then used to calculate the theoretical amplitudes. As a last step, the theoretical amplitudes were fit to those observed using the χ^2 minimisation technique described in Randall et al. (2005).

The results, shown in Fig. 2, indicate a unique solution for the two main pulsation modes of V391 Peg. The 349.5 s period is a radial mode: $\chi^2(l=0)=1.5$, $\chi^2(l=1)=53.6$, $\chi^2(2 \leq l \leq 5)>170$. The 354.1 s period is a dipole mode and again there is only one solution compatible with the data: $\chi^2(l=1)=2.5$, $\chi^2(l=2)=17.1$, $\chi^2(l=0)=47.4$, $\chi^2(3 \leq l \leq 5)>180$. These numbers translate into a value of the quality-of-fit parameter (Press et al. 1986) $Q \ll 0.001$ for both modes when we use an l value different from 0 and 1 respectively.

4 Discussion

Thanks to the high quality of the data, this is the first time that the mode degree index has been uniquely identified from multicolor photometry for the two main modes of a star as faint as V391 Peg ($V=14.6$). To our knowledge, conclusive results were obtained only for two brighter stars: KPD 2109+4401 ($V=13.4$, Randall et al. 2005, see also Jeffery et al. 2004) and Balloon 090100001, the brightest known sdBV star with $V=12.1$ (Baran et al. 2008, Charpinet et al. 2008).

The results reported in this article confirm that multicolor photometry can set useful identification constraints on the pulsation modes of sdB rapid pulsators, provided that the data have a high enough quality. ULTRACAM on a 4 m class (or larger) telescope is an ideal instrument for such studies.

Acknowledgements. R.S. thanks Stuart Littlefair for his help in data reduction. R.S. acknowledges support from HELAS for participating to this conference.

References

- Baran, A., Pigulski, A., O'Toole, S.J.: 2008, MNRAS 385, 255
- Bear, E., Soker, N.: 2010, MNRAS submitted (arXiv:1003.4884v1)
- Benatti, S., Silvotti, R., Claudi, R., et al.: 2010, AN in press (these proceedings)
- Charpinet, S., Fontaine, G., Brassard, P., et al.: 1997, ApJ 483, L123
- Charpinet, S., Fontaine, G., Brassard, P., et al.: 2008, ASP Conf. Ser. 392, 297
- Dhillon, V.S., Marsh, T.R., Stevenson, M.J., et al.: 2007, MNRAS 378, 825
- Han, Z., Podsiadlowski, Ph., Maxted, P.F.L., Marsh, T.R., Ivanova, N.: 2002, MNRAS 336, 449
- Han, Z., Podsiadlowski, Ph., Maxted, P.F.L., Marsh, T.R.: 2003, MNRAS 341, 669
- Heber, U.: 2009, ARA&A 47, 211
- Jeffery, C.S., Dhillon, V.S., Marsh, T.R., Ramachandran, B.: 2004, MNRAS 352, 699
- Lee, J., Kim S.-L., Kim C.-H., et al.: 2009, AJ 137, 3181
- Lenz, P., Breger, M.: 2005, CoAst 146, 53
- Littlefair, S.P., Dhillon, V.S., Marsh, T.R., et al.: 2008, MNRAS 391, L88
- Lutz, R., Schuh, S., Silvotti, R., et al.: 2009 A&A 496, 469
- Østensen, R., Solheim, J.-E., Heber, U., et al.: 2001, A&A 368, 175
- Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T.: 1986, Numerical Recipes (Cambridge: Cambridge Univ. Press)
- Qian, S.-B., Zhu L.-Y., Zola, S., et al.: 2009, ApJ 695, L163
- Randall, S.K., Fontaine, G., Brassard, P., Bergeron, P.: 2005, ApJS 161, 456
- Schuh, S., Silvotti, R., Lutz, R., et al.: 2010, Ap&SS tmp 130S (DOI 10.1007/s10509-010-0356-4)
- Silvotti, R., Janulis, R., Schuh, S., et al.: 2002, A&A 389, 180
- Silvotti, R., Schuh, S., Janulis, R., et al.: 2007, Nature 449, 189
- Soker, N.: 1998, AJ 116, 1308